Antiflow of K_s^0 Mesons in 6A GeV Au + Au Collisions

P. Chung,[1] N. N. Ajitanand,[1] J. M. Alexander,[1] M. Anderson,[5] D. Best,[3] F. P. Brady,[5] T. Case,[3] W. Caskey,[5] D. Cebra,[5] J. L. Chance,[5] B. Cole,[10] K. Crowe,[3] A. Das,[2] J. E. Draper,[5] M. L. Gilkes,[1] S. Gushue,[1,8] M. Heffner,[5] A. S. Hirsch,[6] E. L. Hjort,[6] L. Huo,[12] M. Justice,[4] M. Kaplan,[7] D. Keane,[4] J. C. Kintner,[11] J. Klay,[5] D. Krofcheck,[9] R. A. Lacey,[1] J. Lauret,[1] M. A. Lisa,[2] H. Liu,[4] Y. M. Liu,[12] R. McGrath,[1] Z. Milosevich,[7] G. Odyniec,[3] D. L. Olson,[3] S. Y. Panitkin,[4] C. Pinkenburg,[1] N. T. Porile,[6] G. Rai,[3] H. G. Ritter,[3] J. L. Romero,[5] R. Scharenberg,[6] L. Schroeder,[3] B. Srivastava,[6] N. T. B. Stone,[3] T. J. M. Symons,[3] T. Wienold,[3] R. Witt,[4] J. Whitfield,[7] L. Wood,[5] and W. N. Zhang[12]

(E895 Collaboration)

[1]*Departments of Chemistry and Physics, SUNY, Stony Brook, New York 11794-3400*
[2]*The Ohio State University, Columbus, Ohio 43210*
[3]*Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[4]*Kent State University, Kent, Ohio 44242*
[5]*University of California at Davis, Davis, California 95616*
[6]*Purdue University, West Lafayette, Indiana 47907-1396*
[7]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
[8]*Brookhaven National Laboratory, Upton, New York 11973*
[9]*University of Auckland, Auckland, New Zealand*
[10]*Columbia University, New York, New York 10027*
[11]*St. Mary's College, Moraga, California 94575*
[12]*Harbin Institute of Technology, Harbin, 150001 People's Republic of China*

(Received 25 February 2000)

We have measured the sideward flow of neutral strange (K_s^0) mesons in 6A GeV Au + Au collisions. A prominent antiflow signal is observed for an impact parameter range ($b \lesssim 7$ fm) which spans central and midcentral events. Since the K_s^0 scattering cross section is relatively small in nuclear matter, this observation suggests that the in-medium kaon vector potential plays an important role in high density nuclear matter.

PACS numbers: 25.75.Ld

The production and properties of strange particles can provide an important probe of hot and dense nuclear matter [1,2]. They can give insight into the fundamental aspects of chiral symmetry restoration at high baryon density and/or temperature, as well as information relevant to neutron stars [3–6]. Recent theories of kaon propagation in nuclei all predict an important role for the in-medium kaon-nucleon potential [7–11]. This potential is comprised of two parts: (1) an attractive s-wave scalar interaction, which can be linked to chiral symmetry breaking via the mass of the strange quark, and (2) a vector potential which is thought to be repulsive for kaons but attractive for antikaons.

The repulsive kaon-nucleon interaction can lead to a net repulsion of kaons away from nucleons resulting in the antiflow of the kaons [12]. In fact, it has been argued that the sideward and elliptic flow patterns of kaons in relativistic heavy ion reactions can provide a good probe for the influence of both the vector and scalar components of the kaon potential [12,13]. A recent measurement has indicated essentially zero sideward flow for the K^+'s and K_s^0's produced in 1.93A GeV ^{58}Ni + ^{58}Ni collisions. This result has been attributed to the repulsive nature of the kaon-nucleon potential [14]. However, an alternative interpretation involving rescattering effects has been shown to account for the data [15]. The observation of an out-of-plane or negative elliptic flow of K^+ mesons in 1A GeV Au + Au collisions has been associated with the repulsive part of the K^+N potential [16]. Nonetheless, a general consensus on the nature of the kaon-nucleon potential has not been reached.

Flow measurements for K_s^0 mesons can serve as a unique probe of the kaon-nucleon potential in that they avoid possible complications which could result from the Coulomb interaction between a charged kaon and the associated emitting system. Such measurements have been sparse because the relatively short lifetime τ of the K_s^0 ($c\tau = 2.68$ cm) imposes the requirement of a large acceptance device with high detection efficiency and very good momentum resolution. In this Letter we report on the use of such a device—the E895 Time Projection Chamber (TPC) [17]—to make detailed measurements of the flow of neutral strange K_s^0 mesons in 6A GeV Au + Au collisions. The data from these measurements show prominent signatures for the antiflow of K_s^0 for both central and midcentral collisions, suggesting significant in-medium effects for these particles. The kaon potential, rather than that of the antikaon, is expected to dominate in the present study, since relativistic quantum molecular dynamics (RQMD) [18] calculations suggest an antikaon $\bar{K}^0$ contribution of $\lesssim$10% in our data sample. Preliminary results from this work have been reported [19].

 0031-9007/00/85(5)/940(4)$15.00

The measurements have been performed with the E895 detector system at the Alternating Gradient Synchrotron at the Brookhaven National Laboratory. This system includes a TPC [17] and a multisampling ionization chamber [20]. Details on the detector system have been reported earlier [21,22]. The data presented here reflect the excellent coverage, continuous 3D tracking, and particle identification capabilities of the TPC. All are important for the efficient detection and reconstruction of the neutral strange K_s^0 mesons.

The K_s^0's have been reconstructed from their pion decay daughters $K_s^0 \rightarrow \pi^+ + \pi^-$ (branching ratio ~69%) using the following procedure. First, all TPC tracks in an event were reconstructed along with the calculation of an overall event vertex. Second, each $\pi^+\pi^-$ pair was considered and their point of closest approach calculated. $\pi^+\pi^-$ pairs whose trajectories intersected at a point other than the main vertex were then evaluated to yield invariant mass m_{inv} and momentum. All of these hypothesized K_s^0's with $0.4 < m_{\mathrm{inv}} < 0.6$ GeV/c^2 were then passed through a fully connected feedforward multilayered neural network [23] trained to separate "true" K_s^0's from the combinatoric background. The network was trained from a set consisting of true K_s^0's and a set consisting of combinatoric background, respectively. True K_s^0's were generated by tagging and embedding simulated K_s^0's in raw data events in a detailed GEANT simulation of the TPC. The background or "fake" K_s^0's were generated via mixed events in which the candidate daughter particles of the K_s^0 ($\pi^+\pi^-$) were chosen from different data events.

The resulting experimental invariant mass distribution for K_s^0's is shown in Fig. 1. The distribution has been obtained for central and midcentral events (charged particle multiplicity ≥100) in which one or more K_s^0's have been detected. This multiplicity distribution is estimated to correspond to an impact-parameter range, $b \lesssim 7$ fm. The distribution shown in Fig. 1 is clearly peaked at the invariant mass expected for the K_s^0 (~0.5 GeV), and the excellent peak to background ratio clearly demonstrates the reliability with which the neural network is able to separate real K_s^0's from the combinatoric background. Figure 2a shows the uncorrected (for detection efficiency) decay-length distribution in the rest frame of the K_s^0's, i.e., $d_i/\gamma_i\beta_i$, where d_i is the laboratory distance from the main vertex to the decay vertex of each K_s^0, i. The distribution is shown for the same K_s^0's used to construct the invariant mass distribution shown in Fig. 1. The distribution is characterized by a prominent exponential tail. The apparent deficit below $ct \sim 4$ cm reflects the difficulty of K_s^0 reconstruction in the region of high track density near the main event vertex. An exponential fit to the data over a region for which the detection efficiency was determined to be constant (7–11 cm) yields a $c\tau$ value of 2.74 ± 0.07 cm. This value is close to the expected value of 2.68 cm and therefore serves as further confirmation that the neural network does indeed separate true K_s^0's from the combinatoric background. The reconstruction procedure produces a raw yield of ~0.03 K_s^0's per event.

It is important to establish that the procedure used to train the neural network does not lead to the spurious "creation" of K_s^0's. To do this, we have processed fake

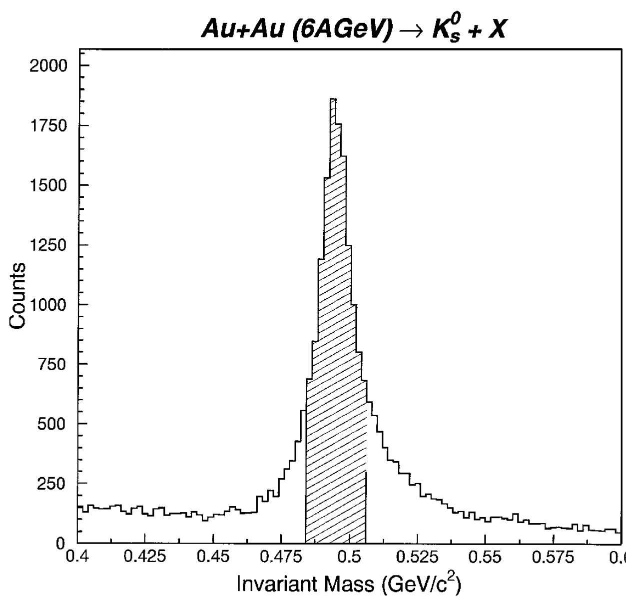

FIG. 1. Invariant mass distribution for K_s^0. The hatched area indicates accepted K_s^0 particles.

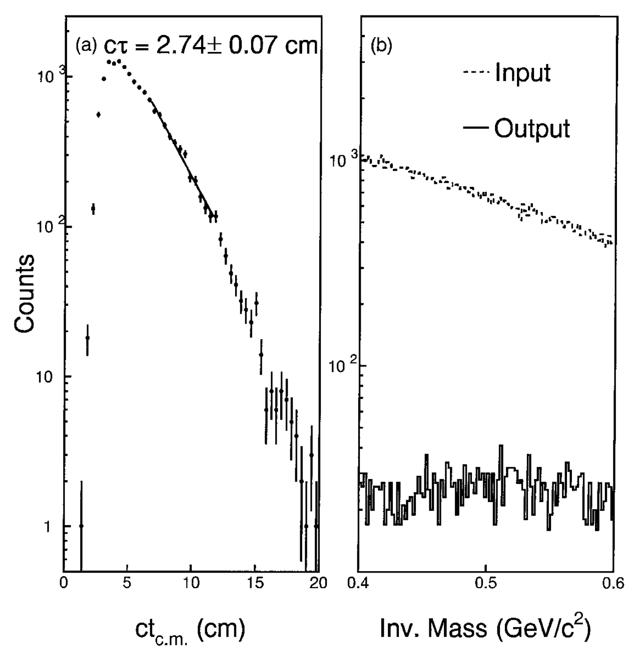

FIG. 2. (a) Decay-length distribution in the rest frame of the K_s^0. The solid curve is an exponential fit to the data (see text). (b) Invariant mass distributions for combinatoric events processed by the neural network (see text). The input and output distributions are represented by the dotted curve and solid curve, respectively.

K_s^0's through the neural network. Figure 2b shows input (dashed histogram) and output (solid histogram) invariant mass distributions for fake K_s^0's generated via the mixed event procedure discussed above. The absence of a peak (at the K_s^0 mass) in the output distribution demonstrates that the neural network is properly trained and does not "create" spurious K_s^0's.

Our flow analysis, which follows the standard transverse momentum analysis technique of Danielewicz and Odyniec [24], employs a gate, $0.485 \leq m_{\mathrm{inv}} \leq 0.505$ GeV, centered on the invariant mass peak to ensure a relatively pure sample (~90%–92%) of K_s^0's (~12 060 K_s^0's above background). The gate is represented by the hatched area shown in Fig. 1. The orientation of the reaction plane vector $\mathbf{Q}$ was determined for each event i, by summing over protons and light nuclei (j), with charge $Z \leq 2$ in events associated with a selected impact-parameter range [25]; $\mathbf{Q}_i = \sum_j^n w(y_j)\mathbf{p}_j^t/|\mathbf{p}_j^t|$. Here, $\mathbf{p}_j^t$ and y_j represent the transverse momentum vector and rapidity, respectively, for baryon j. The weight $w(y_j)$ is assigned the value $\langle p^x\rangle/\langle p^t\rangle$, where $\langle p^x\rangle$ is the transverse momentum in the reaction plane for baryons. $\langle p^x\rangle$ is obtained from the first pass of an iterative procedure. The orientation of the impact parameter vector is random. Therefore, the distribution of the determined reaction plane should be uniform (flat). We have established that deviations from this uniformity are the direct result of deficiencies in the acceptance of the TPC and have applied rapidity and multiplicity dependent corrections following Ref. [21]. Such corrections ensure the absence of spurious flow signals which could result from distortions in the reaction plane distribution. The dispersion of the reaction plane, $\langle\phi_{12}\rangle/2$, is estimated via the the subevent method [24] to be ~37° and ~33° for central and midcentral events, respectively.

The mean transverse momenta $\langle p^x\rangle$, of K_s^0's in the reaction plane are shown as a function of the normalized c.m. rapidity, y_0, in Fig. 3. Here $y_0 = y_{\mathrm{Lab}}/y_{\mathrm{c.m.}} - 1$; y_{Lab} is the rapidity of the emitted particle in the Lab, and $y_{\mathrm{c.m.}}$ is the rapidity of the c.m. The $\langle p^x\rangle$ value shown for each rapidity bin (filled stars) in Fig. 3 includes a small correction for (a) the effect of the ~8%–10% combinatoric background and (b) inefficiencies associated with the detection of the K_s^0. The correction for the combinatoric background has been made by evaluating the $\langle p^x\rangle$ (for each rapidity bin) for the experimental combinatoric background followed by a weighted subtraction of these values from the $\langle p^x\rangle$ values obtained for the invariant mass selection indicated in Fig. 1. It is important to note here that the magnitude of the flow for the combinatoric background is on average ~4–5 times smaller than that for the K_s^0's. Thus, the net effect of the background would be an apparent reduction in the flow. The procedure employed to evaluate the flow is as follows. First, for each rapidity selection, we evaluate the $\langle p^x\rangle$ as a function of p^t over the range 0–0.7 GeV/c. For this p^t range the $\langle p^x\rangle$ shows a linear dependence (on p^t) with a negative slope. Following this evaluation, we determine and correct the K_s^0 p^t distributions for the same rapidity selection. Estimates for these efficiency corrections have been obtained by tagging and embedding simulated K_s^0's (with a flat input p^t distribution for each y) in raw data events in a detailed GEANT simulation of the TPC. Subsequently, a weighted average (obtained by folding the corrected p^t distribution with the p^t dependence of $\langle p^x\rangle$ for that y bin) was performed to obtain the $\langle p^x\rangle$ as a function of rapidity selection. It is noteworthy that this procedure takes account of an ~10% correction to the flow resulting from the detection efficiency for K_s^0's.

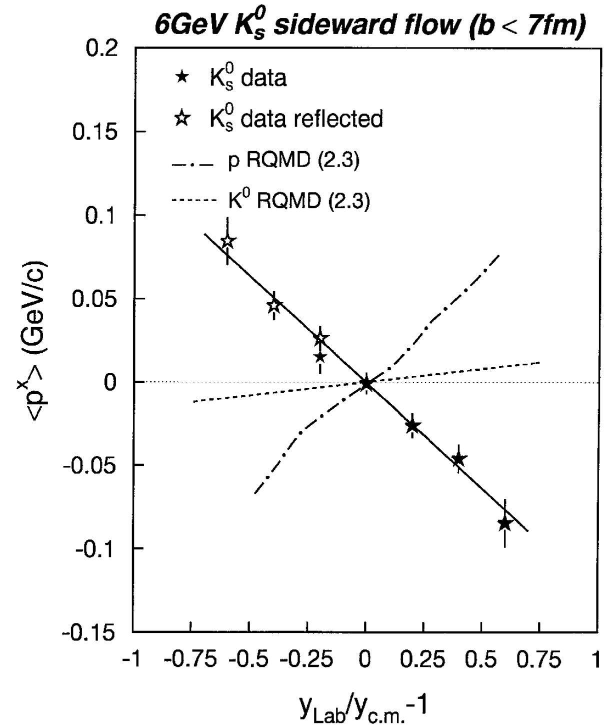

FIG. 3. Experimental $\langle p^x\rangle$ vs y_0 for K_s^0 mesons (stars). $\langle p^x\rangle$ values have been corrected for reaction plane dispersion. The solid curve represents a linear fit to the data. Error bars are statistical. The dot-dashed and dotted curves represent results obtained for protons and K_s^0's from RQMD v (2.3) (with mean field). The RQMD results have been obtained for the same impact parameter and p^t selection as that for the data.

The representative $\langle p^x\rangle$ values shown in Fig. 3 are for $p^t \leq 700$ MeV/c, and $b \lesssim 7$ fm. The limited acceptance for K_s^0 detection at negative rapidities results in an apparent cutoff for $y_0 \leq -0.30$. The $\langle p^x\rangle$ values clearly follow an antiflow pattern. Similarly prominent antiflow patterns have been obtained for more central and less central events. A correction factor of 1.44 has been applied to the data shown in Fig. 3 to account for the reaction plane dispersion [26–28]. A linear fit to these data yields a slope of -127 ± 20 MeV/c. The dotted and dot-dashed curves shown in Fig. 3 represent flow results obtained from RQMD [18] calculations for K_s^0's and protons, respectively. The calculations, which have been performed for the same impact parameter and p_t range as that for the data, include the effects of a mean field, as well as rescattering. However, they do not include the kaon-nucleon potential. Figure 3 shows calculated trends for protons which are in qualitative agreement with the data [29]. By contrast, the experimental flow pattern observed for K_s^0's is clearly at odds with the results obtained from the calculations. This difference is particularly striking for the comparison of both the magnitude and sign of the flow. Here, it is important to stress that unlike pions, K_s^0's have a long mean free path in nuclear matter due to their rather small scattering cross section ($\sigma_{K^0+p} \sim 10$ mb and $\sigma_{\pi+p} \sim 100$ mb). This being the case, one cannot account for the antiflow of K^0's via the reabsorption mechanism commonly exploited to explain pion antiflow [30]. Thus, we attribute the disagreement between data and theory to the absence of an appropriate kaon-nucleon potential in RQMD and conclude that the experimentally observed flow pattern (for K_s^0's) is more consistent with predictions for a strong influence of the repulsive kaon vector potential in the nuclear medium [12,13].

In sum, we have measured the transverse flow of neutral strange K_s^0 mesons in central and midcentral 6*A* GeV Au + Au collisions. The data show a clear antiflow signal which is in stark contrast to that observed for protons at the same beam energy. This contrast is more pronounced than for lower energies and a smaller system size [14], possibly because the effects of the repulsive kaon mean field become more significant with the higher baryon densities expected at 6*A* GeV. Our sidewards flow data, while apparently different from those for the ^{58}Ni + ^{58}Ni system (1.93*A* GeV) [14], are not incompatible with the conclusions drawn about the role of the vector potential.

This work was supported in part by the U.S. Department of Energy under Contracts No. DE-AC03-76SF00098 and No. DE-AC02-98CH10886, and Grants No. DE-FG02-89ER40531, No. DE-FG02-88ER40408, No. DE-FG02-87ER40324, and No. DE-FG02-87ER40331; by the U.S. National Science Foundation under Grants No. PHY-98-04672, No. PHY-97-22653, No. PHY-96-01271, No. PHY-96-05207, and No. INT-92-25096; by the University of Auckland Research Committee, NZ/USA Cooperative Science Programme CSP 95/33; and by the National Natural Science Foundation of People's Republic of China under Grant No. 19875012.

[1] C. M. Ko and G. Q. Li, J. Phys. G **22**, 1673 (1996).
[2] S. A. Bass *et al.,* J. Phys. G **25**, R1 (1999).
[3] G. E. Brown *et al.,* Nucl. Phys. **A567**, 937 (1994).
[4] G. Q. Li *et al.,* Nucl. Phys. **A625**, 372 (1997).
[5] V. Thorsson *et al.,* Nucl. Phys. **A572**, 693 (1994).
[6] J. W. Harris *et al.,* Annu. Rev. Part. Sci. **46**, 71 (1996).
[7] D. B. Kaplan *et al.,* Phys. Lett. B **175**, 57 (1986).
[8] G. E. Brown *et al.,* Phys. Rev. C **43**, 1881 (1991).
[9] T. Waas *et al.,* Phys. Lett. B **379**, 34 (1996).
[10] J. Schaffner *et al.,* Phys. Rev. C **53**, 1416 (1996).
[11] M. Lutz, Phys. Lett. B **426**, 12 (1998).
[12] G. Q. Li *et al.,* Phys. Rev. Lett. **74**, 235 (1995); Bao-An Li *et al.,* Phys. Rev. C **60**, 3492 (1999).
[13] Z. S. Wang *et al.,* nucl-th/9809043.
[14] J. Ritman *et al.,* Z. Phys. A **352**, 355 (1995).
[15] C. David *et al.,* Nucl. Phys. A (to be published), nucl-th/9805017.
[16] Y. Shin *et al.,* Phys. Rev. Lett. **81**, 1576 (1998).
[17] G. Rai *et al.,* IEEE Trans. Nucl. Sci. **37**, 56 (1990).
[18] H. Sorge, Phys. Rev. C **52**, 3291 (1995).
[19] E895 Collaboration, P. Chung *et al.,* J. Phys. G **25**, 255 (1999).
[20] G. Bauer *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **386**, 249 (1997).
[21] E895 Collaboration, C. Pinkenburg *et al.,* Phys. Rev. Lett. **83**, 1295 (1999).
[22] E895 Collaboration, D. Best *et al.,* J. Phys. G **23**, 1873 (1997).
[23] M. Justice, Nucl. Instrum. Methods Phys. Res., Sect. A **400**, 463 (1997).
[24] P. Danielewicz and G. Odyniec, Phys. Lett. **157B**, 146 (1985).
[25] Unique separation of π^+'s and protons was not achieved for all rigidities. Consequently, a small fraction of π^+'s were included in the sample used to determine the reaction plane. The small influence of this pion contamination on the extracted flow value is accounted for via the dispersion correction for the reaction plane.
[26] P. Danielewicz *et al.,* Phys. Rev. C **38**, 120 (1988).
[27] J.-Y. Ollitrault, nucl-ex/9711003 v2.
[28] A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C **58**, 1671 (1998).
[29] E895 Collaboration, H. Liu *et al.,* in *Quark Matter '97, Proceedings of the 13th International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, Tsukuba, Japan, 1997,* edited by P. T. Hatsuda *et al.* [Nucl. Phys. **A638**, 451c (1998)]; E895 Collaboration, H. Liu *et al.* (to be published).
[30] H. Oeschler, Institut fur Kernphysik, Darmstadt Report No. 98/20, 1998.